The anomalous change in the QBO in 2015-16

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Key Points:

- The 2015-16 quasi-biennial oscillation had an unprecedented deviation from the 1953-present observational record
- Easterlies unexpectedly appeared in the westerly phase of the quasi-biennial oscillation
- The remaining quasi-biennial oscillation westerlies showed an upward displacement, not the normal downward propagation

Abstract

The quasi-biennial oscillation (QBO) is a tropical lower stratospheric, downward propagating zonal wind variation, with an average period of ~28 months. The QBO has been constantly documented since 1953. Here we describe the evolution of the QBO during the Northern Hemisphere winter of 2015-16 using radiosonde observations and meteorological reanalyses. Normally, the QBO would show a steady downward propagation of the westerly phase. In 2015-16, there was an anomalous upward displacement of this westerly phase from ~30 hPa to 15 hPa. These westerlies impinge on, or "cut-off" the normal downward propagation of the easterly phase. In addition, easterly winds develop at 40 hPa. Comparisons to tropical wind statistics for the 1953-present record demonstrate that this 2015-16 QBO disruption is unprecedented.

1 Introduction

The quasi-biennial oscillation (QBO) is a tropical lower stratospheric, downward propagating zonal wind variation, with an average period of ~28 months, but its period is variable by more than a year between the shortest and longest QBO periods. Ebdon [1960] and Reed et al. [1961] independently first detected the QBO. Tropical radiosonde wind observations that document the QBO have been made continuously since 1953 [e.g., *Naujokat*, 1986]. The importance of the QBO is that it dominates the variability of the tropical lower stratospheric meteorology [*Wallace*, 1973]. The QBO also has an associated temperature and meridional circulation structure. The structure and dynamics of the QBO have been extensively reviewed in *Baldwin et al.* [2001]. Here we report on a significant, anomalous, adjustment of the QBO structure during the Northern Hemisphere (NH) winter of 2015-16: it is the only such disruption to the regular QBO propagation in the data record between 1953 and 2016.

2 Data and Methodology

Radiosondes provide a long-term QBO record. Because of the variation in the length of QBO cycles, composite wind comparisons have been constructed from radiosondes based on the transition from easterly to westerly equatorial winds at 40 hPa and westerly to easterly at 10 hPa for each available QBO cycle. This enables a direct comparison of the length of the QBO westerly and easterly phases for each year. These composites are based on the monthly-mean radiosonde data updated from *Naujokat* [1986] and available at the Freie Universität Berlin (FUB). These monthly means have been derived from three radiosonde stations: Canton Island (Jan. 1953 – Aug. 1967, 3°S and 172°W), Gan/Maledive Islands (Sept. 1967 – Dec. 1975, 1°S and 73°E) and Singapore (since Jan 1976, 1˚N and 104˚E).

The twice-daily wind data derived from the Singapore radiosonde data (WMO station 48698, 1˚N, 104˚E) have been used over the January 1979 to June 2016 period. These Singapore radiosondes are of high quality, long-term (since 1976), and routinely reach levels above 10 hPa. This radiosonde site provides one of the best datasets for monitoring the QBO from the ground. Singapore currently uses the Vaisala VRS92G radiosonde, and Vaisala DigiCORA III sounding system to receive and process the wind information.

Assimilated meteorological fields complement the in-situ wind observations by providing a complete three-dimensional picture of the QBO and its evolution on a regular global grid. Here we use the Modern-Era Retrospective analysis for Research and Applications-Version 2,

MERRA-2 [*Bosilovich et al.*, 2015] that begins in 1980 and is ongoing. MERRA-2 shows realistic QBO structures [*Coy et al.*, 2016], encompassing 14-15 QBO cycles. Time altitude cross sections of the QBO winds from the initial time until 2012 are presented in *Kawatani et al.* [2016]. In MERRA-2, the gravity-wave drag parameterization [*Molod et al*., 2015] generates a QBO, even in the free-running model, so that the resulting assimilation circulations are not based solely on the assimilation of observations. The MERRA-2 instantaneous winds on standard pressure levels [*GMAO*, 2015a] and monthly averaged temperatures on standard pressure levels [*GMAO*, 2015b] were used in this study.

3 Results

The 2015-16 QBO has shown highly anomalous behavior. Figure 1 displays the QBO over the last 36 years (January 1981-July 2016) as computed from monthly-mean zonal wind averages derived from the twice-daily Singapore radiosonde data. The QBO downward progression is clearly seen, with an extended westerly phase in the tropical lower stratosphere [*Reed*, 1962]. The novel behavior of interest here began in the Sept.-Oct. 2015 period (denoted by the semitransparent vertical line in the bottom right of Figure 1). There is an apparent upward displacement of an anomalous westerly winds, which developed at 20 hPa in late 2015 (denoted with the semi-transparent white arrow in Fig. 1). This late-2015 westerly is also accompanied by the development of easterlies in the 30-70 hPa layer. The anomalous westerlies appear to curtail the easterly phase downward propagation that is apparent at 10 hPa in late 2015 and early 2016.

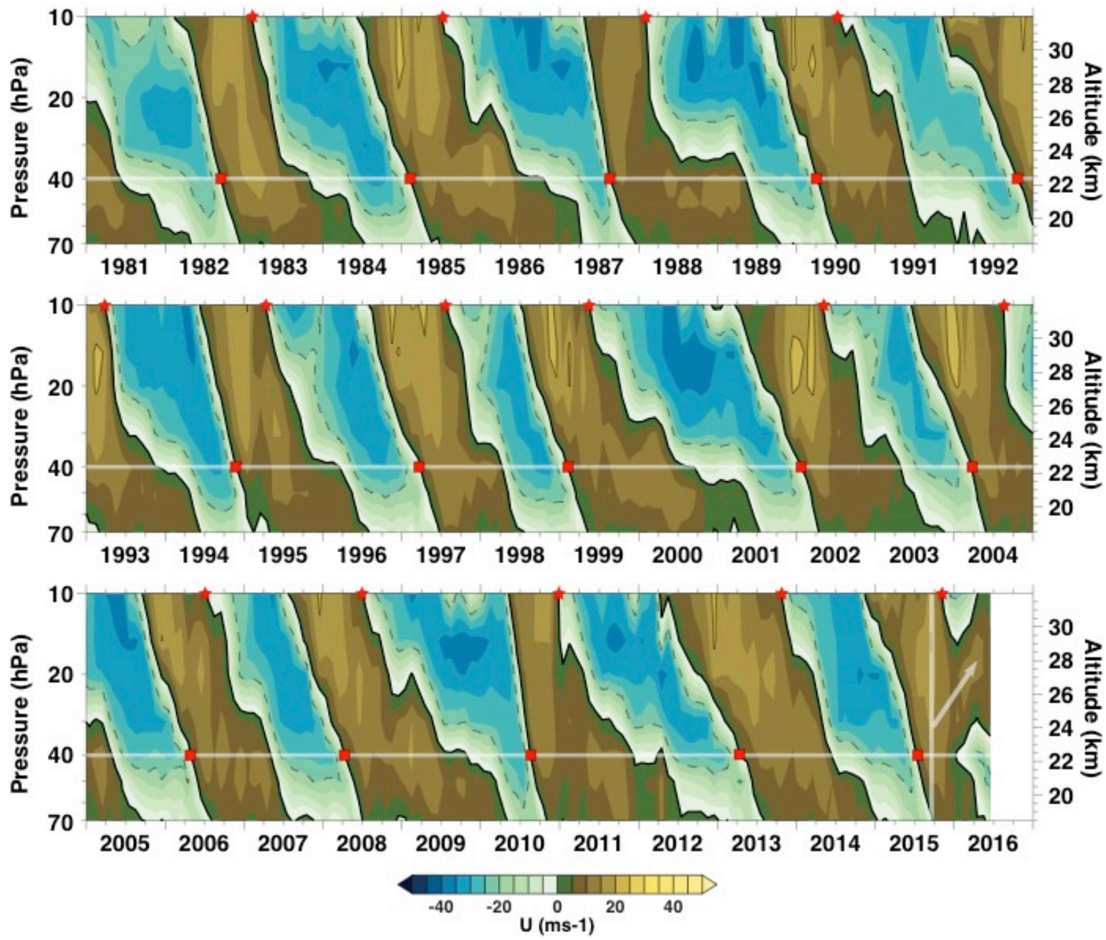

Figure 1. Monthly-mean zonal wind (m s^{-1}) derived from Singapore radiosondes (1˚N, 104˚E) between 70 and 10 hPa for 1981 through July 2016. The color scale is on the bottom with 5 m s^{-1} color increments. Easterlies are shown in cyan-blue, while westerlies are in green-brown. Contours are every 20 m s^{-1}, with easterlies dashed and westerlies solid, and a thick black zero wind. The red squares show the dates of the 40 hPa easterly-to-westerly transition, while the red stars show the 10 hPa dates of the westerly-to-easterly transition.

The development of this QBO anomaly is also evident in the twice-daily radiosondes launched in the tropics from a variety of locations. Figure 2a displays the Singapore radiosonde time series, illustrating the upward westerly wind displacement along with the development of the easterlies that are centered at the 40-hPa level. This 40-hPa easterly reverted back to a westerly in July 2016. This anomalous QBO behavior is also observed at all of the radiosonde sites near the Equator. Examples include Nairobi (WMO 63741, 1.3˚S, 37˚E), Menado (WMO 97014, 1.5˚N, 123˚E), Pontianak (WMO 96581, 0˚N, 109˚E), Fortaleza (WMO 82397, 3.8˚S, 39˚W), and Macada (WMO 82099, 0˚N, 51˚W). The consistency of the westerlies-to-easterlies development at all of the radiosonde locations means that the QBO anomaly cannot be attributed to data errors or radiosonde problems from one station.

The MERRA-2 assimilation includes these radiosonde observations, and yields a similar vertical structure in the zonal mean as shown in Figs. 1 and 2a (not shown). Figure 2b shows the meridional structure of the zonal wind evolution at 40-hPa from MERRA-2 (smoothed with a 10-day running mean). The westerlies develop at 40 hPa in July 2015, with the switch to easterlies in February 2016. While the westerlies appear at the Equator in July 2015, subtropical westerlies also appear at 20˚N in early-November 2015 and persist through mid-April before reversing to easterlies. Westerly zonal mean winds at 40 hPa, 20˚N in the mid-winter accompanied by a QBO westerly phase are not uncommon in the full MERRA-2 record (e. g., 1980-81, 1982-83, 1987-88, 1990-91, 1992-93, 1994-95, 1997-98, 2006-07, 2010-11).

The temporal evolution of this QBO anomaly is relatively slow. However, in addition to the QBO, Kelvin waves are evident in the Singapore radiosonde observations. Fig. 2a shows short time-scale, near-vertical "striping" that is most probably upward propagating Kelvin waves with typical downward phase velocities of ~1 km day^{-1}. The easterlies at 40 hPa first begin to appear in the Singapore data in early December 2015 and this easterly phase is fully developed by mid-April. The zonally averaged data also show a slow evolution at 40 hPa. Hence, this easterly anomaly develops in a steady but unusual manner by a mechanism (or a combination of mechanisms) that supplies a steady forcing. Another feature of the anomalous 2015-16 QBO is the 40-hPa location of the developing easterlies. Model and data studies of the QBO generally place the tropical stratospheric zonal mean wind accelerations in regions of strong vertical wind shear, conducive to the deposition of momentum by vertically propagating equatorial waves, and producing the signature descending shear zones [*Baldwin et al.*, 2001; *Holt et al.*, 2016]. In contrast, Figs. 1 and 2a show that the easterlies develop in the strongest region of the westerlies where the vertical wind shear is relatively small, suggesting that an anomalous forcing mechanism may be in play.

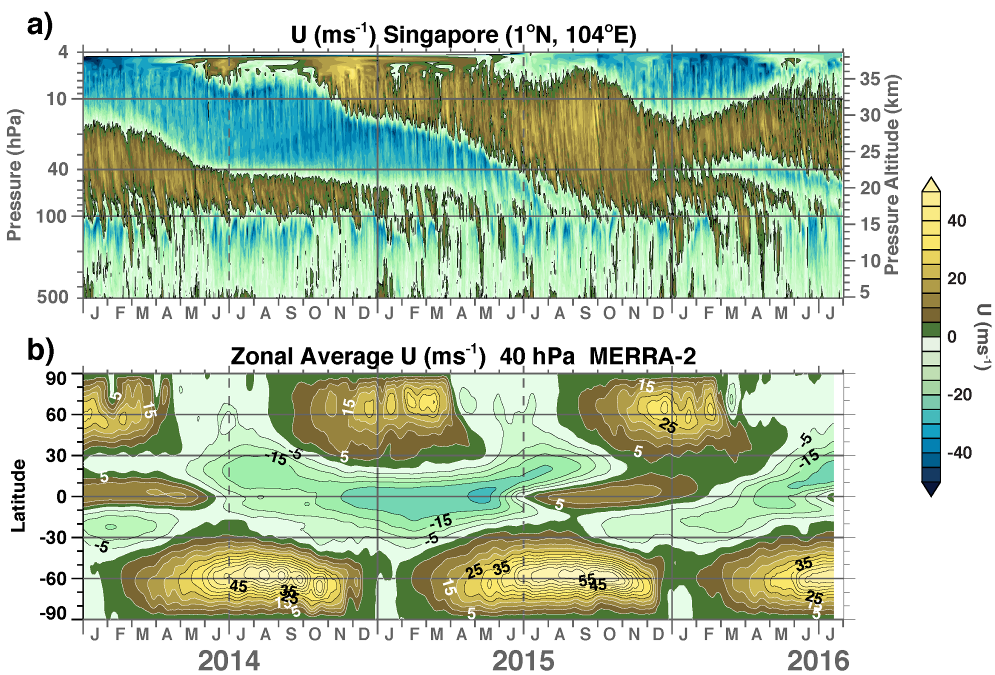

Figure 2. Daily zonal winds (Jan. 2014 through July 2016) for (a) altitude-time plot of Singapore radiosondes, and (b) latitude-time plot of MERRA-2 zonal-mean zonal winds at 40 hPa. Easterlies are shown in cyan-blue, while westerlies are in green-brown.

No similar QBO anomaly has ever been observed. The long-term QBO FUB dataset [*Naujokat*, 1986] has been used to construct a composite of the QBO over the 66 years between 1953 and 2016. This period includes 27 easterly-to-westerly transitions at 40 hPa, effectively describing 26 complete oscillations, with an average QBO duration of 27.6 months as measured between the easterly-to-westerly transitions. Easterly-to-westerly transitions at 40 hPa are shown as red squares in Figure 1, while westerly-to-easterly transitions are shown as red stars in Figure 1. Figure 3 shows zonal wind composites around these transition dates for 10 hPa (Fig. 3a) and 40 hPa (Fig. 3c). The transition dates for each QBO are phase rectified to the same date to create the QBO composites. In Fig. 3c, the average line shows the 40-hPa easterly phase is typically ~12 months, while the average duration of the 40-hPa westerly phase is 15.3 months (excluding the 2015-16 QBO event, which lasted for only six months). The previous earliest reversal to easterlies was in the 1959-1960 QBO (a 10-month westerly phase). The behavior of 2015-16 was near normal during the easterly phase, but within a few months of switching to westerlies this phase began to switch back to easterlies. The 2015-16 QBO at 40 hPa was thus highly anomalous and well outside the previous observational range for the westerly phase.

The 10-hPa level also showed the highly anomalous rapid phase reversal. Fig. 3a shows a comparable pattern to the 40-hPa level, but for westerly to easterly transitions. The easterly phase appears in 2015, but reverses in about five months back to westerlies (see Fig. 1). As at the 40-hPa level, this 10-hPa transition is well outside the range of the historic observations record.

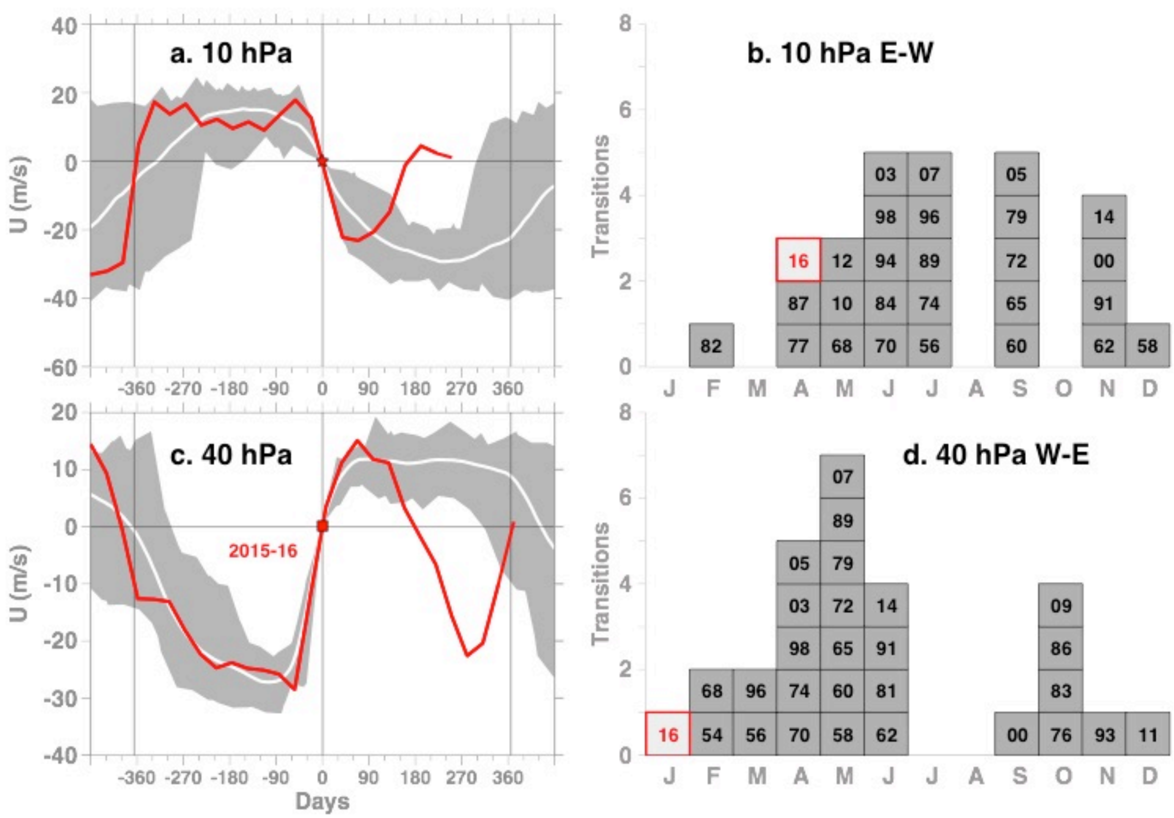

Figure 3. Composite of monthly zonal winds around the QBO transition time from the FUB Singapore-Canton Island-Gan/Maledive Island time series at: (a) 10 hPa, and (c) 40 hPa. As noted in the text, the time of the transition is calculated from the QBO time series (27 events), and each event is then shifted to this "day 0" (i.e., phase rectified). Transition dates are noted in Figure 1 as red squares for 40 hPa E-W and red stars for 10 hPa W-E. The white line shows the average of the 27 events, while the grey shading shows the minimum to maximum range of all of the QBOs (excluding the 2015-16 event). The 2015-16 event is plotted in red. The vertical black lines show ±1 year. Also shown in the right panels are the months when: (b) the easterly to westerly transition occurs at 10 hPa, and (d) the westerly to easterly transition occurs at 40 hPa. In b) and d) the boxes are labeled by year with 2016 highlighted in red.

The westerly to easterly phase change at 40 hPa occurred in January 2016. Figure 3d displays the months of the phase changes for the westerlies-to-easterlies for all years using the FUB radiosonde data set (following *Pawson et al*., 1993). The 2015-16 QBO anomaly stands out as having the only transition in January for the 28 phase transitions. Most of the 40-hPa transitions occur in the NH spring or fall periods. The 10-hPa easterly-to-westerly transition occurred in April 2016, but is not anomalous with respect to many other easterlies-to-westerlies phase transitions during the NH spring to early summer.

The structure of the 2015-16 QBO anomaly appears to have a similar spatial structure to a normal QBO phase, as can be seen in the zonal mean winds and temperatures. Figure 4 displays the (4a) zonal mean wind deviations and (4b) temperature deviations derived by averaging the zonal means over Jan. through May 2016 and subtracting them from the 1980-2015 time average over this same Jan-May period. The easterly anomaly centered at 40 hPa is only a few kilometers in depth, as is clear in Figs. 1 and 2. The westerly anomaly is centered at about 20 hPa, and is somewhat deeper. As with most QBOs, the easterly-westerly structure is symmetric about the equator covering the zone from 15˚S to 15˚N. It is also notable that westerly wind anomalies dominate the upper troposphere-lower stratosphere (UTLS, 100-70 hPa) in a region that usually has rather weak winds. The Fig. 4 white lines show the zonal-mean zonal wind from MERRA-2 for Jan.-May 2016. As is also seen in Figure 2, a westerly wind is apparent in the sub-tropics (20˚N) in the lower stratosphere (100-40 hPa) during this period (up to 40 hPa at 25˚N for example). The wind structure in the troposphere is also found to be somewhat anomalous with stronger than average easterly winds in the 900–500 hPa layer associated with the 2015-16 ENSO (El Niño–Southern Oscillation**)** event.

In addition to the wind deviations, the mean circulation induced by this anomalous QBO zonal winds also modifies the temperatures. The 2016 temperature deviations from the 1980-2015 average (Fig. 4b) show the vertical and latitudinal anomalies associated with the equatorial zonal wind vertical shears with cooling below and warming above the 40 hPa easterlies along with the oppositely signed temperature perturbations at 15˚S and 15˚N produced by the mean circulation response to the equatorial winds. This temperature pattern is typical of the mean circulation response to QBO-like equatorial wind changes with altitude [*Plumb and Bell*, 1982]. Note that the implied positive vertical motion perturbation (adiabatic cooling) in the upper part of the 20-hPa westerlies may explain at least part of the anomalous upward displacement of the westerlies seen in Fig. 1. The Jan.-May 2016 tropical tropospheric temperatures are much warmer than the Jan.-May 1980-2015 average, while the stratosphere temperatures are generally cooler than the Jan.-May 1980-2015 average.

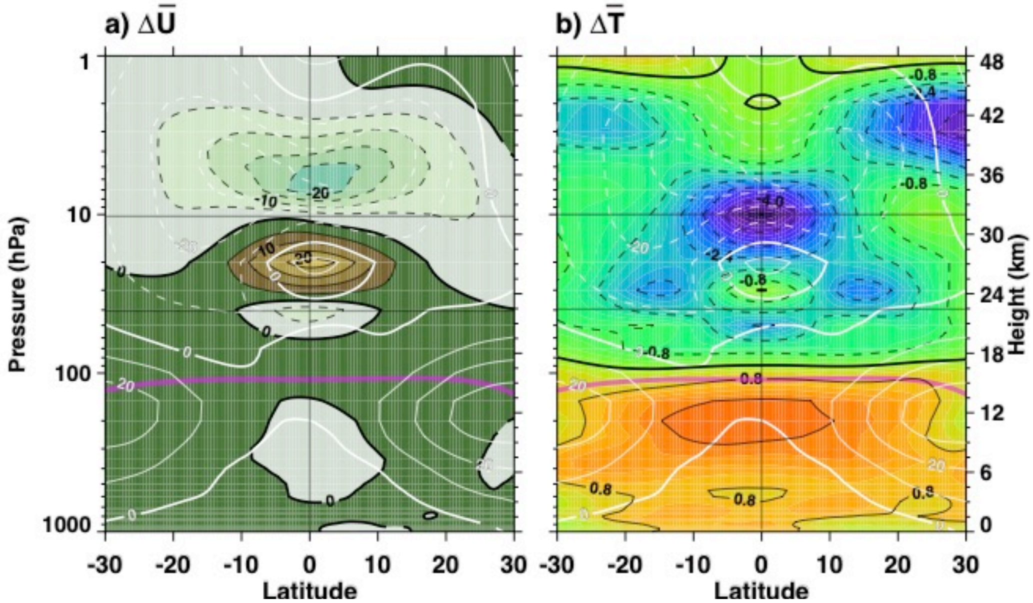

Figure 4. The Jan.-May 2016 deviations from the Jan.-May 1980-2015 average of (a) zonal-mean zonal wind and (b) temperature, as computed from MERRA-2. Both panels have the Jan.-May 2016 averaged zonal mean zonal winds (white lines) and tropopause (thick magenta line). Units are m s^{-1} and K.

4 Summary and Conclusions

The QBO dominates the variability of the tropical stratospheric zonal winds and has impacts on the interannual variability throughout the stratosphere. The 2015-16 equatorial zonal winds revealed a rapid and highly anomalous QBO phase change in a manner that is unprecedented in the historic (66-year) data record.

This QBO anomaly appeared as an “upward displacement” of the westerly phase, accompanied by the development of easterlies at 40 hPa. This westerlies upward displacement appeared to “cut-off” the normal downward propagation of the easterlies, resulting in the shortest 10 hPa easterly phase ever observed in the 1953-2016 record. In a corresponding manner, the easterlies at 40 hPa appeared below this upward displaced westerly, resulting in the shortest westerly phase ever observed in the 1953-2016 record. By the May-late July 2016 period, the QBO appeared to have resumed a normal downward propagation.

This QBO anomaly began developing in December 2015, and was fully complete by mid-April 2016. The anomaly’s evolution was relatively steady over the course of this period, suggesting a steady forcing mechanism (or a combination of mechanisms) that supplied a steady forcing. In addition, this QBO anomaly was distinguished by the development of easterlies in the strongest region of the westerlies, where the vertical wind shear was relatively small.

Clues to the causes of this QBO anomaly are found in the wind and temperature structure. First, the westerlies at 40 hPa extend from the subtropical jet axis (~30˚N) to the Equator for an extended period. The absence of a critical line (zero wind line) would allow propagation of

planetary scale Rossby waves from the NH mid-latitudes into the tropical region, where they could deposit additional easterly momentum. Second, the anomalous easterlies develop in a weak wind-shear, this suggests an anomalous forcing mechanism since the QBO is normally driven by momentum deposition from upward propagating waves in high wind-shear levels. Third, the tropical troposphere was much warmer than the 1980-2015 average, while the stratosphere was colder than the 1980-2015 average. This thermal structure was likely a combined result of both the strong 2015-16 ENSO and climate effects.

The QBO is a regular feature of the climate system with predictable skill beyond three years [*Scaife,* 2014]. However, the QBO's predictability is based on models adjusted to imitate its relatively regular past record. The anomalous 2015-16 QBO evolution may prove to be a challenge to future predictability studies.

Because of the unprecedented nature of this anomalous 2015-16 QBO and its importance to the stratosphere, it is crucial to begin analysis of its causes and implications for the stratospheric-tropospheric system. We plan to continue investigating several aspects of the QBO anomaly, including the dynamical forcing, the evolution of stratospheric trace gases, and the possible relationships to ENSO and climate change. In particular, the role of mid-latitude Rossby wave dynamical forcing on the equatorial winds will be studied with the complete MERRA-2 set of diagnostics. Past barotropic model results have highlighted the ability of Rossby waves to sharpen tropical westerly shear zones without changing the magnitude or location of the equatorial westerlies [*O'Sullivan*, 1997]. MERRA-2 based diagnostics can determine if such a mechanism was modified during the boreal 2015-16 season.

Acknowledgments and Data

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